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ORIGINAL RESEARCH

AN ELECTROMYOGRAPHIC STUDY OF THE VASTII MUSCLES DURING OPEN AND CLOSED KINETIC CHAIN SUBMAXIMAL ISOMETRIC EXERCISES

L. Spairani, PT[1]
M. Barbero, PT[4]
C. Cescon, MEng, PhD[4]
F. Combi, BSS[3]
T. Gemelli, BSS[3]
G. Giovanetti, BSS[2,3]
B. Magnani, MD[1,2]
G. D'Antona, MD, PhD[2,5]

ABSTRACT

Background: Rehabilitation programs for patients with patellofemoral dysfunction aim to recruit the vastus medialis obliquus muscle (VMO) in an attempt to reduce pain and to improve patellar tracking.

Objectives: The aim of the present study was to use surface EMG to assess the effectiveness of two isometric submaximal contractions (10% and 60% of maximal voluntary contraction, MVC) in promoting preferential activation of VMO over vastus medialis longus (VML) and vastus lateralis (VL) in open and closed kinetic chain isometric exercises with the knee joint fixed at 30, 60 and 90 degrees of flexion.

Methods and Measures: Surface electromyography (EMG) signals were recorded with linear adhesive arrays of four electrodes from fourteen healthy young men (age 23.5 ± 3.2, mean±SD) during isometric knee extension contractions at 10% and 60% of the maximum voluntary contraction (MVC) for 1 min and 20 s respectively at 30, 60 and 90 degrees of knee flexion. Initial values and rate of change (slope) of mean frequency (MNF), average rectified value (ARV) and conduction velocity (CV) of the EMG signal were calculated.

Results: Comparisons between the force levels produced at 10% and 60% MVC revealed that the initial values of ARV and CV for the VL, VML and VMO muscle were greater at 60% MVC compared to 10% MVC (3-way ANOVA; $F = 536$; $p < 0.001$, $F = 49$: $p < 0.01$ for ARV and CV respectively). Comparisons between the different muscles demonstrated lower initial values of CV for VMO compared to VL and VLM at 10% and 60% of MVC ($F = 15$; $p < 0.05$). In addition, initial estimates of ARV were higher for VMO compared to VML at both force levels ($F = 66$; $p < 0.05$). Comparisons between open and closed kinetic chain exercises revealed higher initial estimates of ARV for open kinetic chain knee extension at both force levels ($F = 62$; $p < 0.01$). In addition, the absolute value of MNF slope appeared to increase at higher angles for closed kinetic chain at 60% MVC while it was minimum at 60° degrees for open kinetic chain. No significant differences were observed in the rate of change of CV and MNF among the three muscles.

Conclusions: Based on the results of this study, both open and closed kinetic chain exercise similarly activate the three portions of the quadriceps muscle, suggesting that selective training of the vastii muscle is not achievable in these conditions.

Keywords: Electromyography, patellofemoral joint, quadriceps, strength training

[1] Human Anatomy Unit, Department of Experimental Medicine, University of Pavia, Italy;
[2] LUSAMMR Laboratory Muscle for Motor Activities in Rare Diseases, Sport Medicine Centre, University of Pavia, Italy;
[3] Institute of Motor Sciences, University of Pavia, Italy;
[4] Department of Health Sciences, University of Applied Sciences and Arts of Southern Switzerland, SUPSI, Manno, Switzerland;
[5] Department of Molecular Medicine, University of Pavia, Italy).

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CORRESPONDING AUTHOR
Giuseppe D'Antona, MD, PhD
Department of Molecular Medicine and LUSAMMR, Sport Medicine Centre Voghera, Via Forlanini 6, University of Pavia, 27100 Pavia, Italy
Ph: +39 0382 987252
Fax: +39 0382 987664
Email: gdantona@unipv.it

INTRODUCTION

Patellofemoral Pain Syndrome (PFPS), a generic descriptor for anterior knee pain, is a frequent musculoskeletal complaint among adolescents and young adults related to a large spectrum of patellofemoral joint disorders.[1] In presence of PFPS, athletes typically describe pain in the anterior knee. Pain is related to repetitive high-frequency overload of the joint and is aggravated by uphill and downhill walking/running or prolonged flexing of the knees.[2] Once the patellofemoral joint becomes irritated, secondary subchondral bone degeneration, retinacular nerve injury[3,4] chronic retinacular strain[5] or persistent aggravation of the peripatellar synovium[6] may occur thus leading to unremitting pain in some subjects.[7]

Physical examination, initially oriented to exclude anterior intraarticular pain, tendinitis and synovitis, may reveal patellofemoral malalignment, tenderness at the patellofemoral facets, pain on patellofemoral compression test, crepitus on extension, giving way, or a positive "J" sign.[8]

Several causes may contribute to the genesis of patellofemoral pain including direct trauma, overuse, and, in particular, malalignment. While opinions vary, the most accepted hypothesis for malalignment is the abnormal lateral tracking of the patella,[9] which may be related to a neuromuscular imbalance between the vastus medialis obliquus (VMO) and vastus lateralis (VL) muscles, leading to a decrease in the activation of the VMO muscle.[10] As a consequence of the abnormal patellar tracking an overload of the retinaculum and of the subchondral bone may arise thus contributing to anterior knee pain.[11] Moreover with knee flexion the medial migration of the patella produces a recurrent stretching of the lateral retinaculum that may cause nerve changes such as neuromas and neural myxoid degeneration.[3]

It is widely accepted that PFPS should be initially managed by non-surgical means and as in most overuse injuries, rest and change of the training schedule may be useful.[12]

Standard physical therapy for patients with PFPS utilizes a multimodal approach including: quadriceps strengthening, aerobic conditioning, quadriceps muscle stretching, kinetic chain balancing, orthotic devices, stretching of the lateral retinaculum, taping, and bracing.[7,13-16] Recent authors have suggested that quadriceps muscle deficiency is a major issue in patients with this condition[17,18] and strengthening of the quadriceps plays an important role in the management of PFPS. Rehabilitation protocols have also included exercises to selectively train the VMO which is normally involved in the tracking control of the patella by balancing the lateral forces imposed by the other vastii muscles and those induced by the physiological valgus of the knee.

The four distinct muscles of the quadriceps, identified on the basis of the anatomical and physiological features, contribute to control the patellofemoral joint.[19,20] It is generally accepted that among the vastii the vastus medialis can be subdivided into the VMO and the vastus medialis longus (VML) based on the fiber spatial alignment[21] but currently, disagreement exists regarding whether selective activation of VMO over VML and VL is possible.

In fact, over the past decade only few electromyographic studies[22-24] have demonstrated a higher level of activation of VM than VL muscles during open and closed kinetic chain exercises and no data support the effectiveness of isometric contractions in promoting selective training of VMO. In particular, Cerny demonstrated a higher VM/VL activation ratio during knee extension exercises performed with the subjects in a sitting position with the knee flexed from 30 to 0 degrees (full knee extension was 0 degrees) and the hip maximally medially rotated.[25] A relatively higher activation of VM than VL was also observed at 40 degrees of semisquat with the hip medially rotated 30 degrees[23] and during partial squats with flexion angle from 0 to 50 degrees.[26]

A recent systematic review reported that modifying the lower limb orientation or adding a muscle co-contraction does not preferentially recruit VMO. It included 20 papers with several methodological limitations and no specific information regarding the VMO activation in relation to different knee angles, force levels, and open as well as closed kinetic chain exercise interventions were included.[27]

To date it is not known whether submaximal isometric contractions may be useful to increase the ratio of VMO/VML and VMO/VL activation. Thus, the aim of the present study was to use surface EMG to assess the effectiveness of two isometric submaximal contractions (10% and 60% of maximal voluntary contraction, MVC) in promoting preferential activation of VMO over VML and VL in open and closed kinetic chain isometric exercises with the knee joint fixed at 30, 60 and 90 degrees of flexion.

MATERIALS AND METHODS

Subjects

Fourteen young healthy male subjects (age 23.5 $\pm$ 3.2 years; body mass 80.9 $\pm$ 11.5 Kg, height 181.7 $\pm$ 6.3 cm) volunteered to participate in the study which was conducted at the Interdepartmental Resource Center of Motor and Sports Activities (CRIAMS) of the University of Pavia, (Voghera, Italy). Prior to participation the subjects received a detailed description of the study and gave written informed consent. Leg dominance was assessed with a physical test. The right leg was dominant in each of the subjects. Subjects, free from neuromuscular or skeletal impairments, were recreationally active in different sports: six in rugby, six in soccer, two in volleyball, one in general fitness. During the 24 hours before each experimental session, subjects were asked to refrain from performing strenuous physical activity. The study conformed with the guidelines in the Declaration of Helsinki and the ethical approval for the study was granted by the Institutional Medical Research Committee.

Procedures

One week before the experimental sessions all the enrolled subjects underwent a session to estimate their isometric MVC at each of the selected angles (30, 60 and 90 degrees of flexion) during two different exercises: an open kinetic chain leg extension (Technogym SpA, Gambettola, Italy) and closed kinetic chain leg press (Technogym SpA, Gambettola, Italy). Both the exercises machines were modified to perform isometric contractions at different selected angles and provide real time feedback on force (MuscleLab 4000e, Boscosystemlab S.p.A., Rome, Italy). Subjects performed three maximum voluntary contractions (MVCs) of 3-5 seconds duration separated by 5 minutes of rest for each of the 6 conditions. Verbal encouragement was provided to the subjects to promote higher forces in each trial. The highest value of force recorded over the three MVCs was selected as the reference MVC, and used to calculate the sub-maximal force targets for 10% and 60% used throughout the study.

Subsequently each subject performed a series of tests divided in two parts, during which surface EMG signals were obtained from the VL, VMO, and VML muscles of the dominant leg during voluntary submaximal, isometric muscle contractions. In the first part, using the modified leg extension, subjects performed an isometric contractions of 1 minute duration exerting a force of 10% MVC and 20 seconds exerting a force of 60% MVC (in randomized order) respectively at 30, 60 and 90 degrees of flexion.

In the second part, 1 hour after the end of the first part, subjects performed the same protocol but using the modified leg press. In both parts each test was separated by 10 minutes and continuous verbal encouragement was given during all performance testing. Force signals were recorded with MuscleLab 4000e (Boscosystemlab S.p.A., Rome, Italy). The subject was provided with visual feedback of the force signals in order to maintain 10% and 60% of MVC.

EMG recordings

Single differential surface EMG signals were obtained from the vastii muscles using an adhesive linear array of four electrodes (1 mm wide, 5 mm long, and 10 mm apart, LISiN, Torino - Spes Medica, Battipaglia, Italy). To obtain an optimal placement of the array, EMG signals were detected in a few test contractions during which a non-adhesive array of 16 electrodes was moved over the skin to detect the location of the main innervation zone(s) and tendon regions, as described previously.[28] The orientation of the arrays was selected on the basis of visual signal analysis, choosing the angle of inclination that led to the most similar potentials travelling along the array from the innervation zones to the tendons. The regions where the optimal location for the arrays were identified was treated with abrasive paste. The adhesive arrays were then applied between the innervation zone and distally on the VL, VML, and VMO muscles, following the direction of the muscle fibers. To assure proper electrode-skin contact, 20 μl of conductive paste were spread into the electrode cavities of the arrays with a small spatula. The differential surface EMG signals were amplified (multichannel surface EMG amplifier, EMG-USB, LISiN - OT Bioelettronica, Torino, Italy), band-pass filtered (3-dB bandwidth, 10–750 Hz), sampled at 2048 samples/s per channel, A/D converted on 12 bits, displayed online, and stored for further analysis.

EMG signal analysis

Surface EMG signals were divided in epochs of 0.5 seconds and variables of interest such as mean spectral frequency (MNF, Hz), average rectified value (ARV, μV) and conduction velocity (CV, m/s). were computed off-line with numerical algorithms.[29] The correlation coefficient between the two adjacent double differential signals was obtained to assess the reliability of CV estimates. For each array of four electrodes, three values of ARV and MNF were obtained for each epoch. The average value of each triplet was utilized for further analysis.

Statistical analysis

Linear regression was applied to the data to calculate the initial value and rate of change of MNF, ARV and CV. The linear regression model was shown to fit the experimental data better than the exponential model. This is a common finding for signals obtained during voluntary contractions, particularly for the time course of MNF and CV.[30] Normalized rate of change for each variable was calculated as the percentage ratio between rate of change and initial value. Wilcoxon paired tests were used to compare the initial values of each EMG variable between the two contraction levels. To identify differences in the initial value, rate of change and normalized rate of change between the vastii muscles, a non-parametric analysis of variance (Kruskal–Wallis, test) was used, with muscle as the independent factor. Significant differences revealed by the test were followed by the post-hoc Dunn test. Threshold for statistical significance was set to $p = 0.05$.

RESULTS

Figure 2 shows the initial ARV, MNF and CV estimates for the vastii muscles during submaximal contractions at 10 and 60% of MVC. Table 1 summarizes the chi-square values and the results of the statistical analysis.

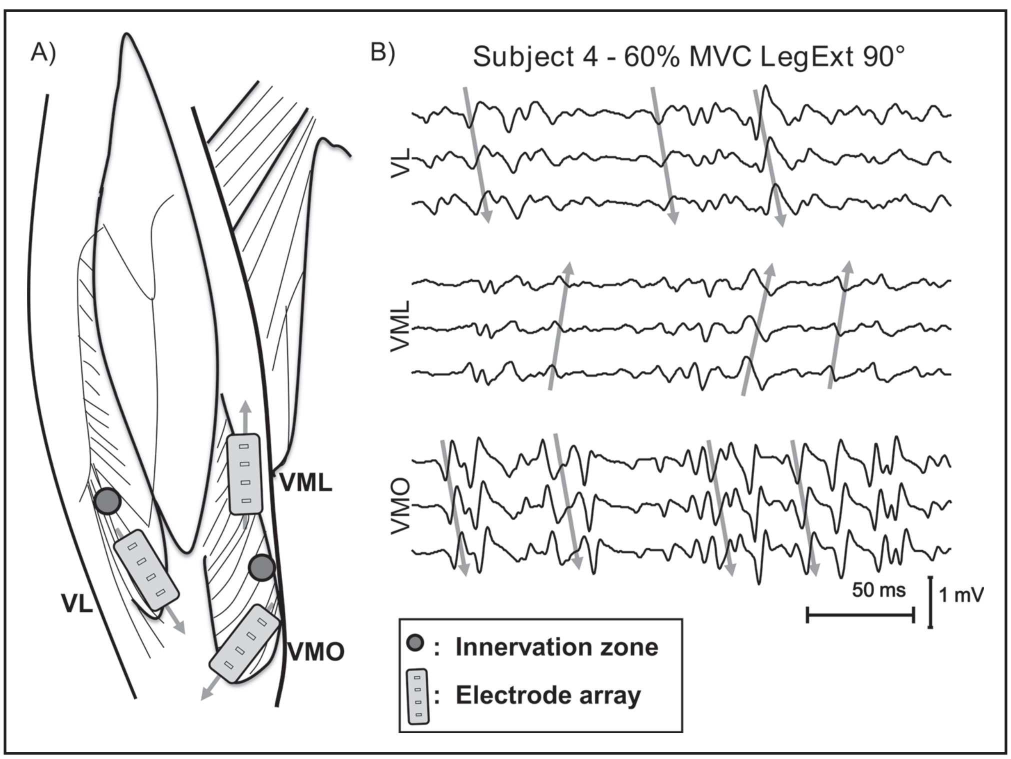

Figure 1. *(A) schematic representation of the electrode array positions on the vastus lateralis and vastus medialis muscles. The arrays and the main innervation zones are shown. (B) Examples of single differential EMG signals detected with the three arrays from one of the subjects during an isometric contraction at 60% MVC on the leg extension (open kinetic chain) with a knee joint angle of 90 degrees. Grey arrows show the propagation of the motor unit action potentials in the EMG signals and in the picture of the muscle.*

In the two sessions, ARV and CV estimates significantly increased with the force level for the three muscles (Kruskal Wallis test; $\chi^2 = 247$; $p = 0.000002$ and $\chi^2 = 30.2$; $p = 0.0016$ for ARV and CV respectively) as expected.

Comparisons between the different muscles demonstrated lower initial values of CV for VMO compared to VL and VLM at 10% and 60% of MVC ($\chi^2 = 8.9$; $p = 0.012$). In addition, initial estimates of ARV were higher for VMO compared to VML at both force levels ($\chi^2 = 39.3$; $p = 0.0007$) (Figure 2). Comparisons between open and closed kinetic chain exercises revealed higher initial estimates of ARV for open kinetic chain knee extension at both force levels for all muscles ($\chi^2 = 31$; $p = 0.0012$).

The rate of decrement of MNF increased significantly ($\chi^2 = 15$; $p = 0.0036$) when angle increased for closed kinetic chain at 60% MVC while it was minimum at 60° degrees for open kinetic chain. No significant differences were observed in the rate of change of CV and MNF for the three muscles ($\chi^2 = 1.7$; $p = 0.32$ and $\chi^2 = 2.5$; $p = 0.37$ for ARV and CV respectively) (Table 1, Figure 3).

DISCUSSION

The level of muscle activation is represented by the EMG signal amplitude while the rate of change or slope of CV and MNF are indicators of muscle fatigue. Although many factors influence these variables, the analysis within subjects allows to determine if a muscle if more active or more fatigue in one or another condition. Furthermore Rainoldi et al showed, using the same methodological approach as used in the current research, that surface EMG signal can be used to describe myoelectric fatigue and functional differences between the vastii muscles.[31]

The authors investigated activation and fatigue in vastii muscles at different knee joint angles during

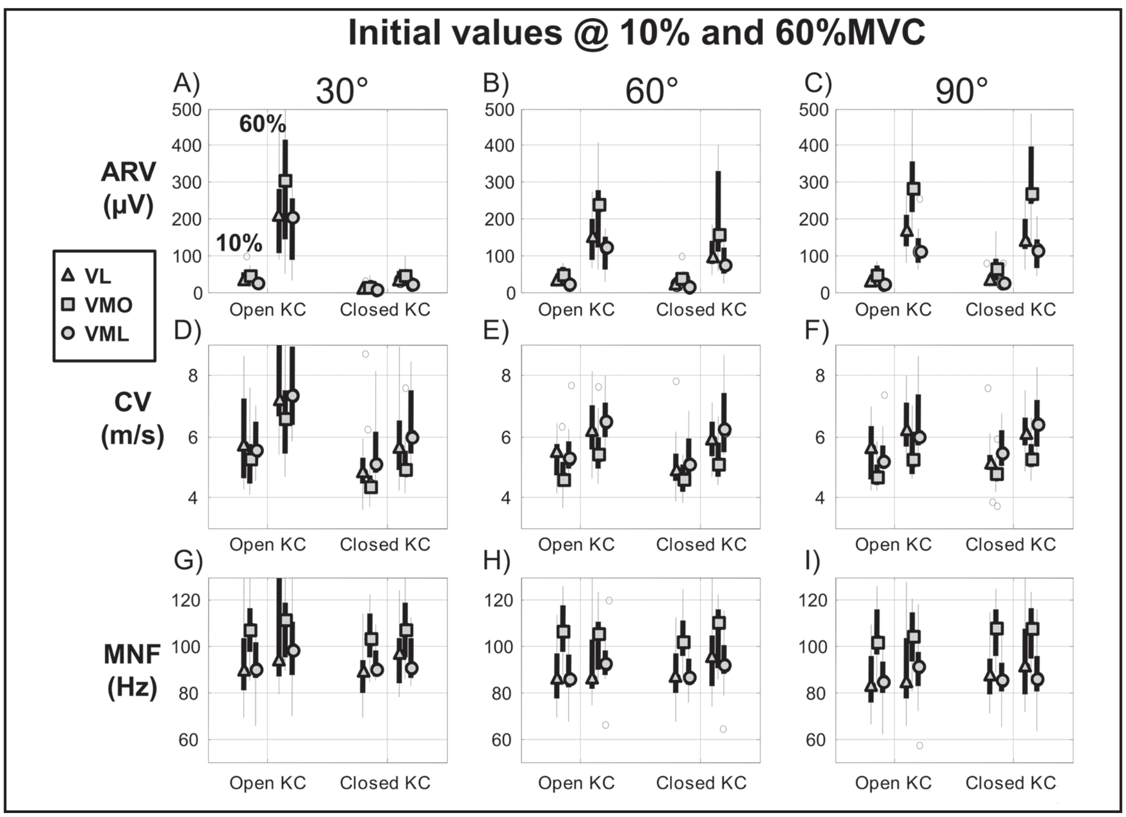

Figure 2. *Initial values of average rectified value (A, B and C), conduction velocity (D, E and F) and mean power frequency (G, H and I) at different knee joint angles (30°, 60° and 90°) respectively. Median, interquartile range and total range are shown for each muscle and each type of exercise at 10% and 60% MVC over the fifteen subjects with box whisker plots. No statistical difference between the muscles was observed in any of the conditions. The three muscles are indicated with different symbols: VL = Δ, VMO = ■, VML = O.*

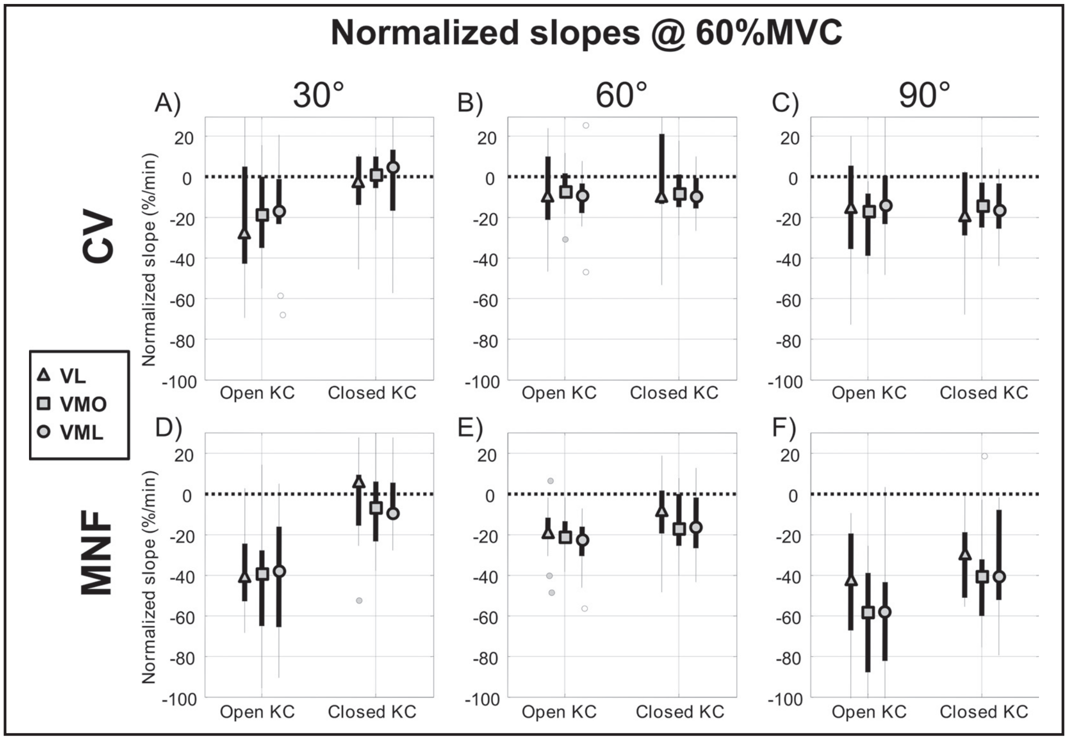

Figure 3. *Normalized slopes of mean power frequency (A, B and C) and conduction velocity (D, E and F) at different knee joint angles (30°, 60° and 90°) at 60% MVC respectively. Median, interquartile range and total range are shown for each muscle and each type of exercise over the fifteen subjects with box whisker plots. No statistical difference between the muscles was observed in any of the conditions. The three muscles are indicated with different symbols: VL = Δ, VMO = ■, VML = O.*

Table 1. *Summary of the non-parametric statistical analysis. Statistical significance is indicated by the use of star symbols (*). The number of stars indicates the significance level: one star (*) for 0.05, two (**) for 0.01, and three (***) for 0.001.*

	Force	Muscle	Open vs Close KC	Angle
ARV init.	$\chi^2 = 247$ p = 0.000002***	$\chi^2 = 39.3$ p = 0.0007***	$\chi^2 = 31$ p = 0.0012**	$\chi^2 = 3.2$ p = 0.064
CV init.	$\chi^2 = 30.2$ p = 0.0016**	$\chi^2 = 8.9$ p = 0.012*	$\chi^2 = 2.6$ p = 0.25	$\chi^2 = 3.1$ p = 0.091
CV slope	$\chi^2 = 1.3$ p = 0.55	$\chi^2 = 1.7$ p = 0.32	$\chi^2 = 0.49$ p = 0.781	$\chi^2 = 3.9$ p = 0.062
MNF slope	$\chi^2 = 2.58$ p = 0.34	$\chi^2 = 2.5$ p = 0.37	$\chi^2 = 1.76$ p = 0.31	$\chi^2 = 15$ p = 0.0036**

open and closed kinetic chain exercises. The isometric exercises were performed during low and high level of force contraction to optimally observe the vastii activation, while the higher level of force (60% MVC) was also used to examine myoelectric manifestations of fatigue. Results showed that the activation of the three portions of the vastus at the selected angles during both open and closed kinetic chain exercise was not significantly different suggesting that the vastii are similarly active throughout the force ranges studied. Additionally the vastii muscles showed no difference in the myoelectric fatigue during all the exercises that were considered.

Surface EMG initial estimates

It is well known that increasing the force output would result in progressively higher CV and MNF estimates[32] and this phenomenon stops at different thresholds below MVC depending on the muscle considered and type of contraction it performs.[33] As expected in all vastii and investigated tasks, comparisons between the two force levels analysed revealed that the initial values of ARV and CV were greater at 60% MVC compared to 10% MVC. On the contrary no changes of the MNF estimates were observed. This evidence may be explained by different responses between CV and MNF during motor unit recruitment.[28]

Interestingly, during open kinetic and closed kinetic chain submaximal isometric exercises the initial value of ARV was greater for the VMO muscle compared to VL and VML. This evidence is in agreement with previously published data highlighting differences in ARV estimates during sustained isometric knee extension contractions at 60% and 80% MVC.[31] The observed changes may possibly reflect intermuscle differences in the motor neuron pool output.[34] Nonetheless discrepancy in the amplitude of surface EMG signals should always be interpreted with caution since they may also be associated with changes in either the shape of the intracellular action potential, volume conductor, sarcolemmal properties of the muscle fibers,[34] or differences in subcutaneous tissue thickness.[35] In fact, a greater subcutaneous tissue thickness would alter the surface EMG estimates resulting in reduced initial ARV and MNF and elevated CV.[35] No data on subcutaneous thickness were collected from the current subjects and the impact of this variable on measured EMG estimates should be a subject for future investigations.

In contrast to ARV, VMO displayed significantly lower initial CV at both force levels in comparison with VML and VL. These differences may be accounted for dissimilar structural and functional features of VMO muscle in comparison with the other vastii. In fact, it is well-known that CV depends on the capacity of voltage-gated sodium channels and Na^+ - K^+ pump[36] and is positively related to the fiber diameter.[37,38] Both these factors may contribute to the observed differences in CV among muscles.

Furthermore, although no data are available on differences in fiber sizes between vastii muscles, the known interrelationship between fiber size, fiber composition and CV should be taken into account.[38] In fact, as both CV and fiber type are related to fiber diameter, these parameters could be intercorrelated because both refer to the same variable (i.e., type II fibers present higher values of CV than type I fibers due to their larger diameter).

Therefore, the different fiber types present in the vastii may account for the observed uniformity in CV values. Biopsy studies demonstrated a significant lower proportion of type II fibres in VM muscles in comparison VL[19] and, among the VM muscles, a lower proportion of type I fibres in VMO in comparison with VML.[19,39,40] Thus, differences in CV values may be explained by diversities in the recruited motor unit pools in which the number of type I fibers with lower CV is higher with respect to type II fibers with higher CV as observed in VMO muscle in comparison with the other vastii. Although this hypothetical explanation is confirmed by the evidence of lower type I and higher type II proportion in VL (higher CV) than in VMO (lower CV), apparently this is not valid for VML. In this muscle a higher CV has been observed despite a higher proportion of type I fibers in comparison with VMO.[19] Notwithstanding these concerns at least two issues should be considered. First, available data on muscle composition of the vastii are based on potentially misleading analysis that does not account for the relative proportions of hybrid fibers, containing more than one myosin isoform and thus differently contributing to the overall detectable CV value.[19] Second, available data on muscle composition of the vastii has been examined in untrained subjects and it cannot be excluded that an interchange in fiber type composition may arise following selective training in VMO and VML. In particular as endurance training is known to upregulate sodium channels and the Na^+ - K^+ pump capacity and to shift the muscle composition towards a higher proportion of slower fiber types in the skeletal muscle[41,42] one can speculate that a higher overall endurance of VMO in comparison with VML and VL may also contribute to differences in initial CV values.

Importantly, apart from speculations regarding physiological differences in initial CV values among vastii, is important to highlight that these diversities may be even more pronounced in clinical settings in which non physiological and asymmetric differences in structural and functional features including changes in fiber size and/or muscle composition of the muscles may occur in relation to injury, surgery, or overuse syndromes.

Open versus closed kinetic chain isometric exercise

In all vastii comparisons between open (knee extension) and closed (leg press) kinetic chain exercises revealed higher initial estimates of ARV for open kinetic chain knee extension at both force levels. Such muscle activation during open kinetic chain exercise is in accordance with previous studies[43] and corroborates the idea that overall the open kinetic chain exercises may place higher stress than closed kinetic chain exercises on the patellofemoral joint in the functional range of motion (i.e. during active movements mainly at 35-45 degree angles).[44-46]

Typically, the ideal ratio between VMO and VL EMG activity (VMO:VL ratio) has been described to be 1:1 and, in presence of patellar dysfunction, this ratio tends to decrease.[47] The imbalance in the synergistic pull of VL and VMO may contribute to patella maltracking and the genesis of anterior knee pain. Researcher have suggested that an appropriate method to counteract patella maltracking is represented by preferential VMO strengthening[23,48] but controversy still remains on whether isometric submaximal open kinetic chain exercise is to be preferred to closed kinetic chain exercise.[49]

In this study the closed-chain isometric and open-chain knee extension exercise produced equal activation of VMO and VL with unchanged VMO:VL ratio at both force levels analysed. These findings agree with previous observations which also concluded that closed chain kinetic exercises are equally effective than open kinetic chain exercises in promoting VMO activation in isometric conditions.[25]

Rates of change of EMG estimates during isometric submaximal contractions

MNF was shown to shift towards lower frequencies during increasing fatigue.[29,50-52] MNF decrease has been attributed to the diminished CV as a consequence of local metabolic changes in the working muscle.[53,54] However, the modifications of the motor unit (MU) action potential shape, MU firing rate and synchronisation of MUs may contribute to MNF changes as well.[55-58]

In this study the authors found that during closed kinetic and open kinetic chain exercise the rate of change of MNF increased significantly with increasing angles when muscles were contracted at 60% of the MVC. Interestingly the rate of change appeared minimum for open kinetic exercise at 60° degrees thus identifying this angle as less fatiguing during high activation of the vastii. Finally no significant differences were observed in the rate of change of MNF of the three muscles thus suggesting similar timing of fatigue appearance in VL, VMO and VML during open and closed kinetic chain exercises at 10% and 60% of the MVC at 30, 60 and 90 degrees of knee flexion.

Limitations of the study

The study presents some limitations which should be taken into account before applying the results in the clinical practice. The subject sample was composed only of young healthy men while older patients, females, and especially subjects with PFPS could have different outcomes. Patellar laxity was not evaluated prior to the experiment and this could influence the EMG parameters of the vastii muscles. The composition of muscles was not evaluated with biopsies, thus it was not possible to include considerations of relationship between EMG parameters and fiber types of the vastii muscles.

CONCLUSIONS

The findings of this study indicate that higher initial estimates of ARV for the VMO, VML and VL were found during the open kinetic chain knee extension than during the closed kinetic chain leg press. Furthermore, no preferential activation or myoelectric manifestations of fatigue of VMO over VML and VL (estimated with ARV) is evident during either open or closed kinetic chain submaximal isometric exercises at the force levels analysed (10% and 60% of MVC). Thus, selective training of VMO over VML and VL is not achievable by means of submaximal isometric contractions in the studied conditions.

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